AM-91-477

Pyroxene-garnet equilibration during cooling in the mantle

Douglas Smith, Barbara R. Barron

For deposit: Table 2

American Mineralogist, 76, 11-12, 1950-1963.

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      PROGRAM COOLV3a
C Adapted from Barron (1985, "Diffusion rate estimates
C from pyroxene, Garnet Ridge, Arizona", U. Texas Austin
C master's thesis)
C Modified by D. Smith - this version is of 6/15/90.
C Comments changed in 5/91 by DS
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C The program simulates one-dimensional diffusion of Al
C in an orthopyroxene sphere included within garnet.
C This version sets the wt % Al2O3 at the opx surface by a
C polynomial fit to values calculated by the method of
C Harley (1984). The boundary condition is specific for
C the compositions of the opx and garnet in grain 1, GR1.
C A Crank-Nicholson subroutine is used.

C The program is a descendent of programs of Wilson and Smith
C written in FORTRAN4 to model Fe-Mg in olivine-garnet pairs.
C See Smith and Wilson, 1985, Amer Mineral 70, 30-39.
C This version has been adapted to take advantage of FORTRAN77 and
C some of the extensions available in Absoft MacFortran.
C It runs on a MacPlus, MacSE, or MacII.

C NOT all options in this modified code have been tested!
C Some are simply retained from earlier versions.

      REAL RATES(20), TZEROS(20)
      REAL U(1000), UNEW(1000), X(1000)
      REAL TFINALS(20)
      REAL UINITL(11)
      REAL WPCTAL,C(4) !C contains coefficients for Harley calc
      INTEGER MM,DD,YY,SECONDS !used in date, time subs

C     .....Description of some variables.....
C U is the vector of concentration values, UNEW is the updated
C version, and x is the array of locations at which the
C concentrations are calculated. WPCTAL is the weight % Al2O3
C in the opx at the garnet contact.

C  Data must be read in from the file COOLDA2
C  Results are written into the files COOLOU and COOLPL

          OPEN (UNIT=4,FILE='COOLDA2',STATUS='OLD') !Input
          OPEN (UNIT=5,FILE='COOLOU',STATUS='NEW') ! output to read
          OPEN (UNIT=6,FILE='COOLPL',STATUS='NEW') ! output for plot

      RGAS=8.314
      JJ=1
      II=JJ
      CONVERT=3600.*24.*365.25*1.0E12 !m2/sec to microns2/yr
      TSURF=273.15

          CALL DATE(MM,DD,YY)  !External subS must be on disk
          CALL TIME(SECONDS)
          STARTTIME = SECONDS
```

```
5       FORMAT(/,1X,I2.2,2('/',I2.2),5X,A30,2X,A25) !For date
        WRITE (5,5) MM,DD,YY,'D Smith COOLV3 Harley, 6/15/90',
     1  'for gar 1, GR1, 20 kb'
                        ! MM,DD,YY from external sub DATE

C Read from file 4, titled COOLDA2

        READ (4,*) NX !Number of X values (<1000)

        READ (4,*) DX !X increment in micrometers

        WRITE(5,*)'NX is ',NX,'     DX is ',DX

        DO (I=1,NX)
                X(I)=DX*I
        REPEAT

        READ (4,*) DZERO !Pre-exp diffusivity in m2/sec
        WRITE(5,*)'DZERO in meters2/sec is ',DZERO
        DZERO=DZERO*CONVERT !to microns2/year

        READ (4,*) H !Activation enthalpy for diffusion (j/m)
        WRITE(5,*)'H, Activation Q for diffusion (joules) ',H

        READ (4,*) NMAX    !Max # of steps in cooling
        WRITE(5,*) 'NMAX number of time steps = ',NMAX

        ! Limits for maximum and minimum time steps
        READ (4,*) DTMIN,DTMAX !values in years
        WRITE (5,*) 'DTMIN = ',DTMIN,'   DTMAX =',DTMAX,' YRS'
                !The size of the time step begins at DTMIN and
                ! is scaled upwards as the diffusivity increases
                ! but is never allowed to exceed DTMAX.

        PRESSR = 20000   !       Pressure (units are bars)
        !The Harley T-Al coefficients (array C) must be for this P *****

        READ (4,*) TZERO !Starting T (K)
        WRITE(5,*)'TZERO starting T(deg K) ',TZERO,
     1  '   at PRESSR P(bars) ',PRESSR

        READ (4,*) NT !Number of final temperatures (NT>1 not tested here)
        WRITE (5,*) 'Number of final temps is ',NT

        NR = 1  !Number of cooling rates (NR>1 not tested here)

        READ (4,*) LE !1 is linear, 0 cooling slab, -1 exponential

        WRITE(5,*)'1, linear: 0, slab: -1, exp: LE = ',LE

        READ (4,*) HOLDTIM !Years to hold if 0 or +
                !If negative, then total of cooling + holding
        WRITE(5,*)'HOLDTIM (if -, cooling + holding) ',HOLDTIM


        IF (LE.EQ.0) TSURF = 298 !Surface T for slab model
```

```
C*********Start do loop of multiple final temps and rates *****
        ! This code has been run only with 1 temp and rate.
        DO 240 II=1,NT

        ! II counts the index of the final temperature

        NR=1

        ! JJ counts the index of the cooling rate

        ! After first pass, skip following entry of
        ! temperatures and cooling rates
        ! If LE=1, then rate in deg/year
        ! If LE=0, then depth in slab in km
        ! If LE=-1 then characteristic rate 1/yr

        IF (II*JJ.EQ.1) THEN
          READ (4,*) (TFINALS(K),K=1,NT) !Final T must be neg
                ! or else years to cool
          WRITE (5,*)'TFINAL (K) or years to cool if positive '
          WRITE(5,*) (TFINALS(K),K=1,NT)
          READ (4,*) (RATES(K),K=1,NR)
          WRITE (5,*)'RATE (K/a) or depth or characteristic rate'
          WRITE(5,*) (RATES(K),K=1,NR)
        ENDIF

        WRITE (5,*)'    '

        PRINT*,'File COOLDA2 has been read; calculations underway'

        ! Now set the final temperature TFINAL and RATE
        TIME=0.
        NTF=II
        TFINAL=TFINALS(II)
        RATE=RATES(JJ)
        TEMP=TEMPTLE(TZERO,RATE,TIME,LE,TSURF)
        NSTEPS=NMAX

C Calculate concentrations using starting temp TZERO
C and a polynomial fit to wt % Al2O3 as f(T) at
C 20 kb based on values calculated with Harley (1984)
C for the compositions in garnet 1 of GR 1
C C(1) = -0.617931      for 18 kb
C C(2) = 1.25765        for 18 kb
C C(3) = -0.894610      for 18 kb
C C(4) = 1.69128        for 18 kb

        C(1) = -0.376626 !C's are fit as f(T/1000)
        C(2) = 0.637697 !they are polynomial coefficients
        C(3) = -0.568287  ! these are fit for 1373 to 873K
        C(4) = 1.46932    !  at 20 kb
        T4 = TZERO/1000.0
        WPCTAL = C(1)+T4*(C(2)+T4*(C(3)+T4*C(4)))

        ! Initialize the concentrations
        DO (I=1,NX)
                U(I)=WPCTAL
        REPEAT
```

```
C Part omitted here for reiterative loop (st 90 etc)

      TOTALT=TFINAL
      IF (TOTALT.LT.0.0) THEN
       TFINAL = - TOTALT
       IF (LE.LT.0) TOTALT=ALOG(TEMP/TFINAL)/RATE
       IF (LE.EQ.0) TOTALT=TOTERF(TZERO,RATE,TSURF,TFINAL)
       IF (LE.GT.0) TOTALT=(TEMP-TFINAL)/RATE
      ELSE IF (TOTALT.GE.0.0) THEN
       TFINAL=TEMPTLE(TEMP,RATE,TOTALT,LE,TSURF)
      END IF

      WRITE(5,*)'Start at T(K) ',TZERO,'  end at ',TFINAL
      IF (LE.EQ.1) WRITE(5,*) 'linear cooling rate'
      IF (LE.EQ.-1) WRITE(5,*) 'exponential cooling',
     *  ' and "rate" is characteristic value'
      IF (LE.EQ.0) WRITE(5,*) '"rate" is depth in km',
     *  ' and cooling slab model was used'
      WRITE(5,*)'Time required ',TOTALT,'  at rate ',RATE
      WRITE(5,*)'Initial wt % Al2O3, WPCTAL, was ',WPCTAL


C     Choose DT value

C DDT is the diffusivity in microns2/year multiplied by DTMIN.
C The time increment (DT) is never allowed to exceed DTMAX.
C DT begins at DTMIN but it is scaled up by a factor of the
C ratio (D at T initial)/(D at last T) at the end of each loop.

      DSTART=DZERO*EXP(-H/(RGAS*TEMP))
      WRITE(5,*)'Initial D (microns2/yr) is ',DSTART
      WRITE(5,*)'Initial D (meters2/sec) is ',DSTART/CONVERT

      DDT=DTMIN*DZERO*EXP(-H/(RGAS*TEMP)) !not exceeded
      DT=DTMIN

      TIME=TIME+DT

C Step through time
      DO (I=1,NSTEPS)
       OLDTEMP = TEMP
       TEMP = TEMPTLE(TZERO,RATE,TIME,LE,TSURF)

       IF (TEMP.LT.TFINAL) EXIT !Beware - an extension to F77

       D = DZERO*EXP(-H/(RGAS*TEMP))
       OLDCO = WPCTAL
       T4 = TEMP/1000.0 ! For Harley opx composition
       WPCTAL = C(1)+T4*(C(2)+T4*(C(3)+T4*C(4)))
       UNEW(NX) = WPCTAL !at boundary with garnet
       U(NX) = UNEW(NX)
       CALL TSTEP (U,UNEW,DX,DT,D,NX,OLDCO)
       DO (J = 1,NX-1)
            U(J) = UNEW(J)
       REPEAT
       OLDSTEP = DT !preserved for output at end
       TIME = TIME + DT
```

```
          TOTALT = TOTALT - DT
          IF (TOTALT.GT.0.) THEN
                DT = DDT/D !lengthens step as D decreases
                IF (DT.GT.DTMAX) DT = DTMAX!limits max time
                IF (DT.GT.TOTALT) DT = TOTALT! finish
          ENDIF

          REPEAT

          WRITE (5,*) I-1,' Steps',TIME,' years'
          WRITE (5,*) 'First time step (yrs) was ',DTMIN,
     1    ' and last step was ', OLDSTEP

C Hold at the current temperature for HOLDTIM
C for 100 steps
          IF (HOLDTIM.EQ.0.) GO TO 220
          TLEFT = HOLDTIM
          IF (HOLDTIM.LT.0.) TLEFT=-HOLDTIM-TIME
          IF (TLEFT.LT.0.) GO TO 220
          TOTALT = TLEFT
          DT = TLEFT/100.
          NHOLD = 100
          DO (I=1,NHOLD)
                CALL TSTEP (U,UNEW,DX,DT,D,NX,OLDCO)
                DO (J=1,NX-1)
                      U(J) = UNEW(J)
                REPEAT
                TIME = TIME + DT
                TOTALT = TOTALT - DT
                IF (TOTALT.LE.0.) GO TO 220
          REPEAT
          WRITE (5,*) NHOLD,' steps',TLEFT,' years'
C  End of holding period
 220      CONTINUE


          WRITE (5,*) 'Elapsed TIME ',TIME,' Final T ', OLDTEMP
          WRITE (5,*)'Final wt % Al2O3 at contact ',WPCTAL
          WRITE (5,*) 'D at final temp (microns2/yr) ',D
          WRITE (5,*) 'D at final temp (meters2/sec) ',D/CONVERT
          WRITE (5,*)' '
          WRITE (5,*) 'Wt % Al2O3 in en'
          WRITE (5,330) (UNEW(J),J=1,NX)

          DO (J=1,NX)
                WRITE(6,340) X(J),UNEW(J)
          REPEAT

 240      CONTINUE  ! end of loop DO 240 II=1,NT
          ! for multiple final temps and rates (not tested)

 330      FORMAT (5(F12.4,2X))
 340      FORMAT (F12.4,F12.4)

          CALL TIME(SECONDS)
          WRITE(5,*)'Seconds for execution = ',SECONDS-STARTTIME

          PRINT*,'Output to files COOLOU and COOLPL'
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      Print*,'Press RETURN to exit this program'

      CLOSE(UNIT=5)
      CLOSE(UNIT=6)
      PAUSE

      END


      SUBROUTINE THOMAS (A,B,C,U,D,N)
C Solve a tridiagonal system by the Thomas method, overwriting
C arrays B and D.  Arrays A, B, C are the lower, middle, upper
C diagonals, U is the unknown, and D is the right hand
C side of the equation.
      REAL A(N), B(N), C(N), U(N), D(N)
      DO (I=2,N-1)
            XMULT=A(I)/B(I-1)
            B(I)=B(I)-XMULT*C(I-1)
            D(I)=D(I)-XMULT*D(I-1)
      REPEAT
      U(N-1)=D(N-1)/B(N-1)
      DO (I=2,N-1)
            U(N-I)=(D(N-I)-C(N-I)*U(N-I+1))/B(N-I)
      REPEAT
      RETURN
      END

      SUBROUTINE TRIAG (QA,QB,QC,UOLD,N,OLDCO)
      REAL QA(N), QB(N), QC(N), UOLD(N), TEMP(1000)
      DO (I=1,1000)
            TEMP(I)=0.0
      REPEAT
      TEMP(1) = QB(1)*UOLD(1) + QC(1)*UOLD(2)
      TEMP(N-1) = QA(N-1)*UOLD(N-2) + QB(N-1)*UOLD(N-1) +
     1 (1.0 + (1.0/(N-1)))*UOLD(N) + (1.0+(1.0/(N-1)))*OLDCO
      DO (I=1,N-3)
            TEMP(I+1) = QA(I+1)*UOLD(I) + QB(I+1)*UOLD(I+1)
     1      + QC(I+1)*UOLD(I+2)
      REPEAT
      DO (I=1,N-1)
            UOLD(I)=TEMP(I)
      REPEAT
      RETURN
      END

      SUBROUTINE TSTEP (UOLD,UNEW,DX,DT,D,N,OLDCO)
C Advance the concentration vector one time step
C by first computing the P matrix, and then solving
C the equation P*UNEW=UOLD for UNEW by the Thomas
C tridiagonal method.
C N is the number of points in the concentration vector
C D is the current diffusivity value
      REAL PA(1000),PB(1000),PC(1000),QA(1000),QB(1000),QC(1000)
      REAL UOLD(N), UNEW(N)
      CALL RCRANK (QA,QB,QC,PA,PB,PC,N,D,DX,DT)
      CALL TRIAG (QA,QB,QC,UOLD,N,OLDCO)
C Now solve the simultaneous equations
      CALL THOMAS (PA,PB,PC,UNEW,UOLD,N)
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```
      RETURN
      END

      SUBROUTINE RCRANK (QA,QB,QC,PA,PB,PC,N,D,DX,DT)
C Radial Crank-Nicholson solution
      REAL PA(N), PB(N), PC(N), QA(N), QB(N), QC(N)
      REAL CONST1,CONST2,APLUS,AMINUS,B
      C=2.0*DX*DX/(D*DT)
      PA(1) = 0.0
      QA(1) = 0.0
      PB(1) = C + 2.0
      QB(1) = C - 2.0
      PC(1) = -2.0
      QC(1) = 2.0
      I1 = 2
C Point I1, to just before the next point I2
      I2 = N-2
      DO (I=I1,I2)
            PA(I) = 1.0/I - 1.0
            PB(I) = C + 2.0
            PC(I) = -1.0/I - 1.0
            QA(I) = 1.0 - (1.0/I)
            QB(I) = C-2.0
            QC(I) = 1.0 + (1.0/I)
      REPEAT
C Do the point at the boundary
      PA(N-1) = -1.0 + (1.0/(N-1))
      QA(N-1) = 1.0 - (1.0/(N-1))
      PB(N-1) = C + 2.0
      QB(N-1) = C - 2.0
      PC(N-1) = 0.0
      QC(N-1) = 0.0
      RETURN
      END

      FUNCTION TOTERF (TZERO,RATE,TSURF,TFINAL)
      ! Compute total time for conductive cooling to TFINAL
      ! Rate is depth in km when LE = 0

      TLOW = 0.0
      TU = 4.0E9 !Search over a 4 Ga interval
      T1 = TLOW
      DO (J=1,10)
            DT = (TU-TLOW)/10. !search increment
            DO (I=1,10)
              TIME = I*DT + TLOW
              TEMP2 =TEMPTLE(TZERO,RATE,TIME,0,TSURF)
              IF (TEMP2.LE.TFINAL) EXIT
              T1 = TIME
            REPEAT
            TU = TIME  !now reset the interval to be searched
            TLOW = T1
      REPEAT
      TOTERF = TU
      RETURN
      END

   FUNCTION TEMPTLE (TZERO,RATE,TIME,LE,TSURF)
```

```
! Compute temperature TEMPTLE at TIME for initial
! value TZERO for a linear decrease (LE = 1),
! or an exponential decrease (LE=-1), or a cooling
! slab model (LE = 0).  For the cooling slab model,
! the rate is the depth in the slab in km and the
! thermal diffusivity is appropriate for the mantle.

      IF (TIME.EQ.0.) THEN
            TEMPTLE = TZERO !avoids dividing by 0 below
      ELSE IF (LE.EQ.-1) THEN
            TEMPTLE=TZERO*EXP(-RATE*TIME)
      ELSE IF (LE.EQ.0) THEN
            TEMPTLE=(TZERO-TSURF)*
     1      ERF(.5*RATE/SQRT(2.641E-5*TIME))+TSURF
      ELSE IF (LE.EQ.1) THEN
            TEMPTLE=TZERO-RATE*TIME
      END IF
      RETURN
      END

      FUNCTION ERF(X) !Press et al., 1989, Numerical Recipes, p 164
      !Returns erf(x) to a fractional error < 1.2e-7
      Z = ABS(X)
      T = 1./(1. + 0.5*Z)
      ERFCC=T*EXP(-Z*Z-1.26551223+T*(1.00002368 +
     *T*(.37409196+T*(.09678418+T*(-.18628806 +
     *T*(.27886807+T*(-1.13520398+T*(1.48851587 +
     *T*(-.82215223+T*.17087277)))))))))
      IF (X.LT.0.) ERFCC = 2. - ERFCC
      ERF = 1 - ERFCC
      RETURN
      END
```

```
75
3.0
3.8
500000.0
1800
100000
4000000
1373
1
1
0
-973.
0.000001
```

The input file, COOLDA2, is above. An annotated version is below.

75	NX, number of x increments
3.0	DX, x increment in micrometers
3.8	DZERO, pre-exponential coefficient for D
500000.0	H, activation enthalpy for D
1800	NMAX, maximum limit of time steps
100000	DTMIN, minimum time step
4000000	DTMAX, maximum time step
1373	TZERO, starting T in degrees K
1	NT, number of final temperatures
1	LE, 1 is linear
0	HOLDTM, years to hold (if positive)
-973.	TFINAL, negative of desired final T (K)
0.000001	RATE, deg/yr (or characteristic rate or depth)

One of the output files "COOLOU" from Smith-Barron program

05/01/91 D Smith COOLV3 Harley, 6/15/90 for gar 1, GR1, 20 kb
NX is 75 DX is 3.00000
DZERO in meters2/sec is 3.80000
H, Activation Q for diffusion (joules) 500000.
NMAX number of time steps = 1800
DTMIN = 100000. DTMAX = 4.000000E+06 YRS
TZERO starting T(deg K) 1373.00 at PRESSR P(bars) 20000.0
Number of final temps is 1
1, linear: 0, slab: -1, exp: LE = 1
HOLDTIM (if -, cooling + holding) .000000
TFINAL (K) or years to cool if positive
-973.000
RATE (K/a) or depth or characteristic rate
1.000000E-06

Start at T(K) 1373.00 end at 973.000
linear cooling rate
Time required 4.000000E+08 at rate 1.000000E-06
Initial wt % Al2O3, WPCTAL, was 3.23065
Initial D (microns2/yr) is 11.3794
Initial D (meters2/sec) is 3.605908E-19
372 Steps 4.000988E+08 years
First time step (yrs) was 100000. and last step was 1.610304E+06
Elapsed TIME 4.000988E+08 Final T 974.512
Final wt % Al2O3 at contact 1.06494
D at final temp (microns2/yr) 1.894517E-07
D at final temp (meters2/sec) 6.003363E-27

Wt % Al2O3 in en

1.6527	1.6526	1.6525	1.6524	1.6522
1.6519	1.6516	1.6512	1.6508	1.6504
1.6499	1.6493	1.6487	1.6481	1.6474
1.6466	1.6458	1.6450	1.6440	1.6431
1.6420	1.6409	1.6398	1.6386	1.6373
1.6359	1.6345	1.6330	1.6315	1.6298
1.6281	1.6263	1.6244	1.6225	1.6204
1.6183	1.6160	1.6137	1.6112	1.6086
1.6059	1.6031	1.6001	1.5970	1.5938
1.5904	1.5868	1.5830	1.5791	1.5749
1.5705	1.5659	1.5610	1.5558	1.5503
1.5444	1.5382	1.5315	1.5244	1.5167
1.5084	1.4994	1.4896	1.4789	1.4670
1.4538	1.4390	1.4222	1.4027	1.3796
1.3516	1.3163	1.2687	1.1980	1.0649

Seconds for execution = 32.0000

Representative electon probe analyses - Smith and Barron

PHN 4803 Representative compositions for P-T calculations										
SiO2	TiO2	Al2O3	Cr2O3	FeO*	MgO	CaO	Na2O	Sum		Data of Mar 21, 1989
57.3	0.00	0.86	0.28	4.86	36.0	0.23	0.05	99.6		Opx
54.4	0.00	2.32	1.44	1.69	16.4	21.3	1.54	99.1		Cpx
42.1	0.00	21.7	2.56	8.25	20.2	4.99	0.00	99.8		Garnet
J34 Representative compositions for P-T calculations										
SiO2	TiO2	Al2O3	Cr2O3	FeO*	MgO	CaO	Na2O	Sum		Data of June 15, 1990
58.3	0.00	0.75	0.22	4.73	35.8	0.22	0.04	100.1		Opx
54.5	0.02	2.36	1.73	1.84	15.8	21.3	1.77	99.3		Cpx
42.2	0.00	21.4	2.65	8.17	20.1	4.90	0.00	99.4		Garnet
42.3	0.00	0.00	0.00	7.70	51.7	0.02	0.00	101.7		Olivine
Garnet 10, GR1 Representative compositions for P-T calculations										
SiO2	TiO2	Al2O3	Cr2O3	FeO*	MgO	CaO	Na2O	Sum		Data of Dec 12, 1986
54.4	0.16	2.06	0.93	1.38	16.4	22.6	1.19	99.1		Cpx 2.8 µm from contact
42.1	0.04	22.1	1.85	8.79	19.3	5.18	0.02	99.4		Gar 2.8 µm from contact
										Data of Oct 31, 1986
41.6	0.00	0.00	0.00	6.29	51.4	0.02	0.00	99.3		Olivine
41.8	0.08	22.2	1.99	8.59	19.3	5.49	0.00	99.5		Nearby Garnet
Garnet 1, GR1 Representative compositions for P-T calculations										
SiO2	TiO2	Al2O3	Cr2O3	FeO*	MgO	CaO	Na2O	Sum		Data of Oct 17, 1986
58.0	0.05	1.06	0.29	3.83	36.6	0.14	0.00	100.0		Opx 2.8 µm from contact
42.2	0.04	22.0	1.71	8.10	19.1	5.50	0.00	98.7		Gar 2.8 µm from contact
										Data of Nov 10, 1986
41.5	0.00	0.00	0.00	5.62	52.4	0.00	0.00	99.5		Olivine
42.3	0.09	22.8	1.73	7.86	20.4	5.25	0.02	100.6		Nearby Garnet
Pr35 Representative compositions for P-T calculations										
SiO2	TiO2	Al2O3	Cr2O3	FeO*	MgO	CaO	Na2O	Sum		Data of Apr 4, 1990
56.7	0.02	0.75	0.06	14.0	30.0	0.11	0.00	101.6		Opx
54.9	0.14	3.71	0.32	4.47	14.1	20.9	2.24	100.8		Cpx
40.2	0.02	22.7	0.41	21.9	10.7	5.08	0.00	101.0		Garnet
Prs90q Representative compositions for P-T calculations										
SiO2	TiO2	Al2O3	Cr2O3	FeO*	MgO	CaO	Na2O	Sum		Data of Apr 24, 1990
56.9	0.00	1.10	0.16	9.08	33.2	0.14	0.00	100.6		Opx
54.1	0.23	5.28	0.88	2.57	14.0	21.2	1.77	100.1		Cpx
41.2	0.02	23.0	0.70	16.1	14.5	5.10	0.02	100.7		Garnet

Representative electon probe analyses - Smith and Barron

Garnet-orthopyroxene traverse Garnet 1, GR1 Navajo field (Garnet Ridge)										
SiO2	TiO2	Al2O3	Cr2O3	FeO*	MgO	CaO	Na2O	Sum	μm	from contact
41.8	0.07	21.7	1.74	7.88	19.5	5.44	0.02	98.1	18.4	start of traverse
42.6	0.06	21.9	1.74	7.93	19.7	5.49	0.00	99.4	17.0	Garnet 1 GR 1
41.7	0.07	21.8	1.74	7.87	19.4	5.55	0.00	98.1	15.6	Data of Oct 17, 1986
42.4	0.07	22.0	1.76	7.90	19.4	5.57	0.00	99.2	14.1	
41.8	0.06	21.7	1.74	7.91	19.4	5.40	0.00	98.0	12.7	On about the same
42.9	0.07	21.8	1.70	8.02	19.5	5.48	0.02	99.4	11.3	diameter as the
41.9	0.05	21.6	1.72	8.05	19.4	5.47	0.02	98.3	9.9	traverse of 6/30/82
42.5	0.06	21.8	1.72	7.98	19.5	5.46	0.02	98.9	8.5	
41.7	0.05	21.8	1.74	8.11	19.3	5.61	0.00	98.3	7.1	
42.5	0.05	21.9	1.68	8.06	19.3	5.42	0.00	98.9	5.7	
41.9	0.05	21.6	1.73	8.06	19.1	5.49	0.00	98.0	4.2	
42.2	0.04	22.0	1.71	8.10	19.1	5.50	0.00	98.7	2.8	
42.1	0.03	21.5	1.75	8.30	19.6	5.42	0.00	98.8	1.4	
48.3	0.03	17.2	1.24	7.20	25.8	4.19	0.02	103.9	0.0	taken as contact
57.3	0.04	1.11	0.27	3.80	36.0	0.17	0.00	98.6	1.4	
58.0	0.05	1.06	0.29	3.83	36.6	0.14	0.00	100.0	2.8	
57.3	0.06	1.13	0.30	3.79	36.2	0.16	0.00	98.9	4.2	
58.0	0.07	1.17	0.31	3.75	36.3	0.19	0.02	99.8	5.7	
57.2	0.08	1.23	0.31	3.92	36.1	0.19	0.02	99.1	7.1	
58.0	0.07	1.22	0.32	3.83	36.1	0.17	0.00	99.7	8.5	
57.2	0.08	1.24	0.30	3.92	35.6	0.18	0.00	98.5	9.9	
57.8	0.08	1.27	0.30	3.81	36.0	0.20	0.02	99.5	11.3	
57.1	0.09	1.27	0.33	3.91	36.0	0.21	0.02	98.9	12.7	
57.8	0.09	1.31	0.33	3.97	36.1	0.20	0.02	99.8	14.1	
57.1	0.09	1.31	0.33	3.85	35.7	0.20	0.02	98.6	15.6	
57.6	0.09	1.33	0.34	3.89	35.7	0.22	0.00	99.2	17.0	
57.1	0.09	1.31	0.34	3.96	35.8	0.22	0.02	98.9	18.4	
57.2	0.09	1.36	0.34	3.99	36.0	0.21	0.02	99.2	19.8	end of traverse
57.2	0.11	1.65	0.39	4.17	35.5	0.27	0.02	99.3	159	central opx

Traverse for 3 elements only across diameter of opx inclusion in Garnet 1, GR1. Data of 6/30/82										
K-values for these data were collected on a 3-spectrometer ARL probe (all other data collected on JEOL)										
Correction factors by reference to complete analyses on 10/17/86: Al2O3 (original estimate)*1.65/1.74										
d (μm)	r (μm)	CaO	FeO	Al2O3	d (μm)	r (μm)	CaO	FeO	Al2O3	
4	222	0.17	3.90	1.19	235	12	0.34	4.21	1.66	d is the original traverse
7	219	0.19	3.95	1.28	247	24	0.35	4.25	1.65	distance
10	216	0.18	3.96	1.31	259	36	0.32	4.32	1.69	r is the radial distance
13	213	0.20	4.02	1.34	271	48	0.32	4.30	1.71	from the center
16	210	0.21	4.05	1.37	283	60	0.33	4.23	1.65	
19	207	0.22	4.07	1.40	295	72	0.33	4.30	1.66	
22	204	0.23	4.08	1.39	307	84	0.32	4.27	1.63	
25	201	0.24	4.05	1.42	319	96	0.32	4.23	1.65	
28	198	0.23	4.09	1.43	331	108	0.32	4.31	1.61	
31	195	0.23	4.11	1.46	343	120	0.32	4.30	1.64	
34	192	0.24	4.08	1.47	355	132	0.32	4.23	1.57	
37	189	0.25	4.07	1.45	361	138	0.30	4.25	1.57	
40	186	0.26	4.18	1.48	367	144	0.32	4.23	1.60	
43	183	0.27	4.13	1.48	373	150	0.31	4.22	1.59	
46	180	0.27	4.16	1.47	379	156	0.30	4.26	1.60	
49	177	0.27	4.17	1.47	385	162	0.31	4.27	1.55	
52	174	0.27	4.15	1.49	391	168	0.29	4.22	1.54	
55	171	0.28	4.17	1.48	397	174	0.30	4.27	1.55	
58	168	0.29	4.18	1.49	400	177	0.28	4.27	1.53	
61	165	0.28	4.15	1.53	403	180	0.29	4.25	1.56	
64	162	0.28	4.15	1.51	406	183	0.30	4.23	1.52	
67	159	0.30	4.11	1.50	409	186	0.28	4.24	1.50	
73	153	0.28	4.19	1.52	412	189	0.28	4.25	1.47	
79	147	0.31	4.15	1.54	415	192	0.28	4.17	1.48	
85	141	0.30	4.14	1.58	418	195	0.27	4.20	1.47	
91	135	0.30	4.18	1.55	421	198	0.27	4.19	1.49	
97	129	0.32	4.20	1.57	424	201	0.26	4.18	1.47	
103	123	0.30	4.18	1.58	427	204	0.24	4.13	1.47	
109	117	0.31	4.23	1.56	430	207	0.24	4.13	1.45	
115	111	0.31	4.23	1.62	433	210	0.21	4.20	1.43	
121	105	0.32	4.20	1.59	436	213	0.22	4.13	1.41	
127	99	0.32	4.22	1.61	439	216	0.20	4.08	1.35	
139	87	0.32	4.21	1.62	442	219	0.20	4.06	1.33	
151	75	0.32	4.24	1.58	445	222	0.18	3.99	1.23	
163	63	0.32	4.20	1.61						
175	51	0.32	4.22	1.65						
187	39	0.34	4.21	1.62						
199	27	0.34	4.29	1.65						
211	15	0.34	4.22	1.63						
223	3	0.33	4.25	1.65						
223	0	0.33	4.25	1.65						

Garnet-Clinopyropxene traverse, Garnet 10, GR 1, Navajo field (Garnet Ridge)										
SiO2	TiO2	Al2O3	Cr2O3	FeO*	MgO	CaO	Na2O	Sum	µm	from garnet contact
47.7	0.06	17.3	1.34	6.84	18.6	9.3	0.24	101.4	0	Contact
53.6	0.13	2.59	0.79	1.52	16.7	22.5	1.09	99.0	1.4	Garnet 10, GR 1
54.5	0.17	2.17	0.90	1.37	16.3	22.7	1.20	99.3	2.8	Data of Dec 12, 1986
53.2	0.18	2.21	1.00	1.42	16.2	22.4	1.21	97.9	4.2	Clinopyroxene
54.3	0.20	2.31	1.04	1.40	16.1	22.5	1.27	99.1	5.7	
53.5	0.19	2.32	1.04	1.44	16.2	22.5	1.28	98.5	7.1	
54.3	0.20	2.40	1.08	1.44	16.0	22.4	1.33	99.1	8.5	
53.9	0.20	2.44	1.12	1.51	16.3	22.4	1.31	99.0	9.9	
54.7	0.20	2.48	1.14	1.47	16.1	22.3	1.38	99.8	11.3	
53.6	0.19	2.49	1.16	1.51	16.3	22.4	1.35	98.9	12.7	
54.4	0.20	2.50	1.15	1.51	16.0	22.3	1.41	99.6	14.1	
53.7	0.21	2.55	1.18	1.51	16.2	22.5	1.41	99.2	16.3	
54.5	0.21	2.56	1.18	1.52	16.1	22.4	1.42	99.8	19.8	
53.8	0.22	2.59	1.24	1.44	16.1	22.5	1.40	99.3	22.6	
54.4	0.20	2.63	1.20	1.46	16.1	22.4	1.44	99.8	25.5	
53.4	0.21	2.65	1.22	1.43	16.1	22.4	1.43	98.8	28.3	
54.2	0.20	2.76	1.25	1.49	16.0	22.4	1.49	99.8	33.9	
53.4	0.20	2.80	1.27	1.51	16.0	22.3	1.51	99.0	39.6	
54.5	0.21	2.87	1.26	1.50	16.0	22.3	1.51	100.1	45.3	
53.9	0.19	2.92	1.25	1.55	16.0	22.2	1.55	99.5	50.9	
54.9	0.20	3.00	1.28	1.54	15.8	22.0	1.56	100.3	62.2	
53.9	0.20	3.06	1.28	1.52	16.0	22.1	1.53	99.6	73.5	
54.5	0.20	3.11	1.30	1.46	16.0	21.9	1.55	99.9	84.9	
53.7	0.20	3.20	1.30	1.50	15.9	22.4	1.60	99.7	96.2	
55.0	0.20	3.26	1.27	1.43	15.7	22.2	1.59	100.6	107	
53.8	0.20	3.01	1.25	1.65	17.0	20.7	1.49	99.1	119	
54.5	0.21	3.34	1.29	1.48	15.7	22.4	1.63	100.4	130	
53.5	0.20	3.34	1.31	1.50	15.8	22.0	1.62	99.2	141	one end of traverse
Garnet-Clinopyropxene traverse, Garnet 10, GR 1, Navajo field (Garnet Ridge)										
SiO2	TiO2	Al2O3	Cr2O3	FeO*	MgO	CaO	Na2O	Sum	µm	from Cpx contact
49.0	0.06	15.7	1.25	6.30	18.6	10.6	0.33	101.8	0	contact
43.0	0.04	22.3	1.76	8.61	19.6	5.26	0.00	100.5	1.4	Garnet 10 GR 1
42.1	0.04	22.1	1.85	8.79	19.3	5.18	0.02	99.4	2.8	Data of Dec 12, 1986
42.8	0.05	22.1	1.89	8.73	19.7	5.11	0.00	100.4	4.2	Garnet
42.1	0.05	22.0	1.92	8.76	19.5	5.19	0.00	99.5	5.7	
42.8	0.05	22.1	1.93	8.73	19.6	5.22	0.02	100.5	7.1	
42.3	0.05	22.0	1.95	8.70	19.5	5.11	0.00	99.6	8.5	
42.7	0.05	22.1	1.98	8.65	19.6	5.22	0.02	100.3	9.9	
42.5	0.05	21.8	1.98	8.70	19.5	5.11	0.02	99.6	11.3	
42.8	0.05	22.1	1.99	8.73	19.7	5.07	0.00	100.4	12.7	
42.0	0.05	21.7	2.00	8.70	19.4	5.07	0.02	98.9	14.1	
42.7	0.06	21.9	2.04	8.72	19.7	5.16	0.02	100.3	15.6	
42.4	0.06	21.9	2.01	8.76	19.4	5.11	0.00	99.6	17.0	
42.5	0.05	22.0	2.05	8.77	19.7	5.16	0.02	100.2	18.4	
42.0	0.06	21.7	2.03	8.63	19.4	5.11	0.02	99.0	19.8	
42.8	0.06	21.8	2.06	8.75	19.7	5.08	0.02	100.3	21.2	

42.3	0.06	21.6	2.07	8.65	19.4	5.07	0.02	99.2	22.6	
42.7	0.06	21.9	2.06	8.74	19.5	5.08	0.02	100.1	24.0	continuation of 12/12/86
41.9	0.06	21.6	2.09	8.72	19.4	5.21	0.02	99.0	25.5	traverse Garnet 10 GR1
42.8	0.06	21.9	2.08	8.68	19.7	5.15	0.02	100.4	26.9	
42.1	0.06	21.7	2.07	8.74	19.5	5.10	0.02	99.3	28.3	
42.8	0.06	21.8	2.09	8.66	19.5	5.16	0.02	100.1	29.7	
42.2	0.06	21.6	2.10	8.75	19.5	5.16	0.02	99.4	38.2	
42.5	0.06	21.8	2.12	8.69	19.5	5.26	0.02	99.9	46.7	
42.2	0.07	21.6	2.12	8.74	19.5	5.27	0.02	99.6	55.2	
42.8	0.07	21.7	2.12	8.67	19.6	5.29	0.02	100.2	63.6	
42.2	0.07	21.6	2.11	8.71	19.5	5.29	0.02	99.5	72.1	
42.4	0.07	21.7	2.13	8.75	19.6	5.27	0.02	100.0	80.6	
42.3	0.07	21.5	2.12	8.69	19.4	5.24	0.03	99.4	89.1	
42.7	0.07	21.6	2.13	8.72	19.5	5.27	0.02	100.0	97.6	
42.1	0.07	21.5	2.13	8.69	19.4	5.24	0.02	99.1	106	
42.7	0.07	21.9	2.17	8.72	19.6	5.34	0.02	100.5	115	
41.8	0.08	21.4	2.14	8.67	19.2	5.23	0.02	98.5	132	
42.8	0.07	21.6	2.13	8.69	19.5	5.32	0.03	100.2	149	other end of traverse
42.0	0.05	21.6	1.98	8.60	19.3	5.04	0.02	98.6	14	repeat a point
SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO*	MgO	CaO	Na_2O	Sum	μm	from Cpx contact

Pr35 websterite Chino Valley, AZ traverses across opx-gar-cpx lamellae										
SiO2	TiO2	Al2O3	Cr2O3	FeO*	MgO	CaO	Na2O	Sum	µm	Pr35
40.88	0.01	22.69	0.41	21.58	10.82	5.34	0.00	101.73	0	start
40.24	0.02	22.72	0.41	21.86	10.71	5.08	0.00	101.03	5	Data of 4/4/90
56.68	0.02	0.75	0.06	13.97	30.01	0.11	0.00	101.59	10	
56.11	0.01	0.85	0.08	13.87	29.85	0.13	0.00	100.91	13	
56.52	0.01	1.05	0.10	13.96	29.41	0.12	0.00	101.17	16	
55.66	0.00	1.14	0.10	14.01	29.51	0.12	0.02	100.55	19	
56.37	0.00	1.23	0.10	14.01	29.39	0.13	0.02	101.24	22	
55.14	0.02	1.40	0.10	13.83	28.96	0.41	0.03	99.89	25	
55.92	0.01	1.30	0.11	14.12	29.26	0.14	0.02	100.88	28	
55.87	0.01	1.36	0.11	14.08	29.15	0.14	0.00	100.72	31	
56.57	0.00	1.25	0.11	13.93	29.21	0.13	0.07	101.26	34	
56.17	0.00	1.05	0.10	13.93	29.35	0.10	0.02	100.72	37	
56.84	0.00	0.81	0.08	13.98	29.33	0.13	0.00	101.17	40	
55.94	0.00	1.03	0.09	13.88	29.57	0.12	0.00	100.62	45	
56.71	0.02	1.09	0.10	13.85	29.61	0.12	0.03	101.53	50	
48.43	0.27	11.50	0.43	8.08	19.74	11.14	0.48	100.07	55	amphibole? and crack
57.09	0.01	0.55	0.06	13.33	29.95	0.12	0.03	101.13	60	
55.92	0.04	0.72	0.05	14.37	29.20	0.17	0.02	100.48	65	
49.19	0.10	14.50	0.31	18.08	20.34	2.42	0.08	105.00	68	
43.34	0.04	23.81	0.29	11.42	8.94	8.51	0.23	96.59	71	
40.65	0.05	22.75	0.37	22.73	10.24	4.82	0.00	101.61	74	end
55.89	0.03	1.33	0.09	14.23	29.26	0.17	0.02	101.01	0	start
55.70	0.02	1.15	0.10	13.96	29.43	0.22	0.00	100.56	5	
55.84	0.02	1.03	0.08	13.74	29.52	0.23	0.00	100.46	10	
40.34	0.05	22.50	0.35	21.94	10.84	4.97	0.00	101.00	15	
42.05	0.02	23.18	0.40	15.06	11.45	8.52	0.08	100.76	21	
55.85	0.03	1.12	0.08	13.91	29.75	0.22	0.02	100.98	25	
55.77	0.03	1.36	0.10	14.16	29.28	0.17	0.03	100.90	30	
55.23	0.04	1.27	0.09	13.94	29.02	0.25	0.02	99.86	35	
56.01	0.04	1.35	0.08	14.17	28.97	0.22	0.02	100.87	40	
55.34	0.07	1.65	0.09	14.23	29.52	0.22	0.02	101.13	45	
55.68	0.07	1.13	0.08	14.02	29.12	0.23	0.02	100.34	50	
54.87	0.14	3.71	0.32	4.47	14.13	20.89	2.24	100.77	55	
54.66	0.14	3.63	0.31	4.39	14.03	20.89	2.17	100.21	60	
54.52	0.11	3.56	0.31	4.27	14.24	21.02	2.20	100.22	65	
54.71	0.12	3.53	0.31	4.29	14.00	20.97	2.14	100.07	70	end
54.80	0.02	1.15	0.10	14.20	29.18	0.18	0.02	99.66	0	start
54.87	0.03	0.83	0.06	13.95	29.37	0.19	0.02	99.31	3	
40.08	0.00	21.16	0.44	20.57	12.33	4.85	0.00	99.43	6	
53.86	0.02	3.16	0.09	14.60	28.29	0.76	0.00	100.78	9	
55.22	0.02	1.00	0.09	14.06	29.43	0.17	0.02	100.01	12	
54.99	0.02	1.13	0.09	14.08	29.31	0.17	0.02	99.80	15	
54.41	0.02	1.22	0.09	14.06	29.20	0.19	0.02	99.19	18	
55.37	0.03	1.25	0.10	13.99	29.39	0.16	0.02	100.31	21	
54.56	0.02	1.24	0.09	13.87	28.92	0.21	0.02	98.93	24	end

Prs90q, websterite xenolith, Chino Valley, AZ data of 4/24/90										
SiO2	TiO2	Al2O3	Cr2O3	FeO*	MgO	CaO	Na2O	Sum	µm	Comments
56.47	0.01	2.49	0.44	9.53	32.0	0.12	0.00	101.05	20	C2 opx 20µm from garnet
54.86	0.03	5.80	0.60	9.84	30.1	0.16	0.03	101.44	105	opx interior
54.94	0.02	4.47	0.54	9.75	30.9	0.19	0.04	100.82	55	C4 back towards C2
56.34	0.02	3.75	0.48	9.72	31.1	0.18	0.02	101.61	44	same line
41.82	0.03	23.16	0.82	15.7	14.7	5.31	0.00	101.60		C1 adjacent garnet
41.78	0.02	23.06	0.74	16.2	14.8	5.05	0.00	101.62		C5 same gar by opx C2
41.91	0.01	22.94	0.86	16.2	14.5	5.33	0.00	101.72		C6 same gar near cpx
54.06	0.22	5.40	1.00	2.61	14.0	21.64	1.75	100.67	20	C7 cpx by garnet
53.74	0.38	7.50	1.00	2.73	13.0	21.16	1.96	101.47	48	into cpx interior on line
52.36	0.39	8.26	1.00	2.96	12.6	20.46	1.99	100.07	66	into cpx interior on line
52.26	0.42	8.40	0.97	3.12	12.6	21.10	1.68	100.60	118	into cpx interior on line
51.45	0.39	8.31	0.94	3.51	12.8	21.37	1.55	100.29	176	central cpx on line
41.76	0.02	23.19	0.60	16.1	14.8	5.06	0.02	101.52	25	gar - trav away from opx
41.04	0.01	23.15	0.61	16.1	14.8	5.14	0.02	100.87	30	gar - trav away from opx
41.72	0.00	23.29	0.64	16.1	14.7	5.18	0.03	101.69	35	gar - trav away from opx
41.50	0.02	23.09	0.61	16.0	14.8	5.24	0.02	101.23	40	gar - trav away from opx
41.45	0.01	23.33	0.59	16.1	14.7	5.33	0.03	101.49	45	gar - trav away from opx
41.05	0.02	23.00	0.70	16.2	14.8	4.94	0.02	100.64	15	gar - towards opx
41.56	0.02	23.13	0.76	16.5	14.7	4.99	0.00	101.60	10	gar - towards opx
41.28	0.00	22.97	0.76	16.5	14.6	5.01	0.02	101.13	5	gar - towards opx
49.64	0.06	17.82	0.35	9.87	16.3	6.49	0.54	101.03	0	gar-opx contact
56.92	0.00	1.10	0.16	9.08	33.2	0.14	0.00	100.58	5	opx - trav from contact
57.02	0.00	1.27	0.18	8.98	33.2	0.15	0.00	100.79	10	opx - trav from contact
56.68	0.01	1.31	0.20	8.94	33.0	0.15	0.00	100.23	15	opx - trav from contact
56.98	0.01	1.37	0.22	8.89	33.0	0.15	0.00	100.57	20	opx - trav from contact
57.66	0.01	1.37	0.23	9.04	32.7	0.13	0.00	101.14	25	opx - trav from contact
56.97	0.02	1.49	0.27	9.19	32.6	0.15	0.00	100.68	30	opx - trav from contact
56.38	0.01	1.53	0.27	9.14	32.5	0.16	0.00	99.94	35	opx - trav from contact
56.75	0.01	1.59	0.26	9.19	32.5	0.14	0.00	100.44	40	opx - trav from contact
56.40	0.00	1.60	0.27	9.16	32.4	0.14	0.00	99.92	45	opx - trav from contact
53.12	0.20	5.08	0.81	2.61	14.2	21.34	1.70	99.09		cpx in contact w opx
54.10	0.23	5.28	0.88	2.57	14.0	21.21	1.77	100.06		cpx in contact w gar